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INSTRUCTOR WORKBOOK
Flexible Link Experiment for LabVIEW™ Users
Standardized for ABET* Evaluation Criteria

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SRV02 educational solutions
are powered by:

LabVIEW
NATIONAL INSTRUMENTS

Course material
complies with:

ABET

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PREFACE

Preparing laboratory experiments can be time-consuming. Quanser understands time constraints of teaching and research professors. That's why Quanser's control laboratory solutions come with proven practical exercises. The courseware is designed to save you time, give students a solid understanding of various control concepts and provide maximum value for your investment.

Quanser course materials are supplied in two formats:

1. Instructor Workbook – provides solutions for the pre-lab assignments and contains typical experimental results from the laboratory procedure. This version is not intended for the students.
2. Student Workbook – contains pre-lab assignments and in-lab procedures for students.

This course material is prepared for users of National Instruments **LabVIEW™** software.

The courseware for Quanser Flexible Link experiment is aligned with the requirements of the Accreditation Board for Engineering and Technology (ABET), one of the most respected organizations specializing in accreditation of educational programs in applied science, computing, science and technology. The Instructor Workbook provides professors with a simple framework and set of templates to measure and document students' achievements of various performance criteria and their ability to:

- Apply knowledge of math, science and engineering
- Design and conduct experiments, and analyze and interpret data
- Communicate effectively
- Use techniques, skills and modern engineering tools necessary for engineering practice

Quanser, Inc. would like to thank Dr. Hakan Gurocak from the Washington State University Vancouver, for rewriting the original manual to include embedded outcomes assessment.

The following material provides an abbreviated example of pre-lab assignments and in-lab procedures for the Flexible Link experiment. Please note that the examples are not complete as they are intended to give you a brief overview of the structure and content of the course materials you will receive with the plant.

TABLE OF CONTENTS

1. INTRODUCTION TO QUANSER FLEXIBLE LINK COURSEWARE SAMPLE

Quanser course materials provide step-by-step pedagogy for a wide range of control challenges. Starting with the basic principles, students can progress to more advanced applications and cultivate a deep understanding of control theories. Quanser Flexible Link courseware covers **topics**, such as:

- Modeling the Rotary Flexible Link using Lagrange
- Find the linear state-space model of the system
- Do some basic model validation
- Design a state-feedback controller using Linear Quadratic Regulator (LQR) algorithm through simulation
- Implement the designed LQR controller on the device
- Compare the simulated and measured closed-loop results
- Assess the behavior of implementing a partial-state feedback controller

Every laboratory chapter in the Instructor Workbook is organized into four sections:

- **Background section** provides all the necessary theoretical background for the experiments. Students should read this section first to prepare for the Pre-Lab questions and for the actual lab experiments.
- **Pre-Lab Questions section** is not meant to be a comprehensive list of questions to examine understanding of the entire background material. Rather, it provides targeted questions for preliminary calculations that need to be done prior to the lab experiments. All or some of the questions in the Pre-Lab section can be assigned to the students as homework.
- **Lab Experiments section** provides step-by-step instructions to conduct the lab experiments and to record the collected data.
- **System Requirements section** describes all the details of how to configure the hardware and software to conduct the experiments. It is assumed that the hardware and software configuration have been completed by the instructor or the teaching assistant prior to the lab sessions. However, if the instructor chooses to, the students can also configure the systems by following the instructions given in this section.

Assessment of ABET outcomes is incorporated into the Instructor Workbook – look for indicators such as A-1, A-2 These indicators correspond to specific performance criteria for an outcome. **Appendix A** of the Instructor Workbook includes:

- details of the targeted ABET outcomes,
- list of performance criteria for each outcome,
- scoring rubrics and instructions on how to use them in assessment.

The outcomes targeted by the Pre-Lab questions can be assessed using the student work. The outcomes targeted by the lab experiments can be assessed from the lab reports submitted by the students. These reports should follow the specific template for content given at the end of each laboratory chapter. This will provide a basis to assess the outcomes easily.

2. INSTRUCTOR WORKBOOK TABLE OF CONTENTS

The full Table of Contents of the Quanser Ball and Beam Instructor Workbook is shown here:

3. BACKGROUND SECTION - SAMPLE

Model

The Rotary Flexible Link model is shown in Figure 2.1. The base of the flexible link is mounted on the load gear of the SRV02 system. The servo angle, θ, increases positively when it rotates counter-clockwise (CCW). The servo (and thus the link) turn in the CCW direction when the control voltage is positive, i.e., $V_m > 0$.

The flexible link has a total length of the link L_l and a mass of m_l. and its moment of inertia about the center of mass is J_l. See the *Rotary Flexible Link User Manual* (in [5]) for the values of these parameters. The deflection angle of the link is denoted as α and increases positively when rotated CCW.
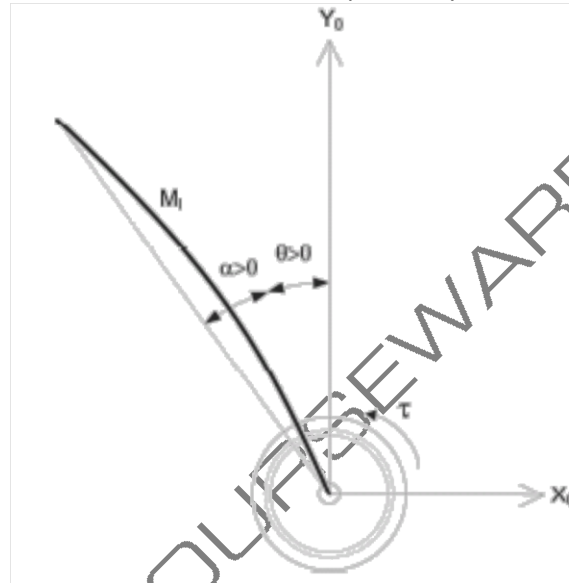

Figure 2.1: Rotary Flexible Link Angles

The flexible link system can be represented by the diagram shown in Figure 2.2. Our control variable is the input servo motor voltage, V_m. This generates a torque, τ , at the load gear of the servo that rotates the base of the link. The viscous friction coefficient of the servo is denoted by B_{eq}. This is the friction that opposes the torque being applied at the servo load gear. The friction acting on the link is represented by the viscous damping coefficient B_l. Finally, the flexible link is modeled as a linear spring with the stiffness K_s.
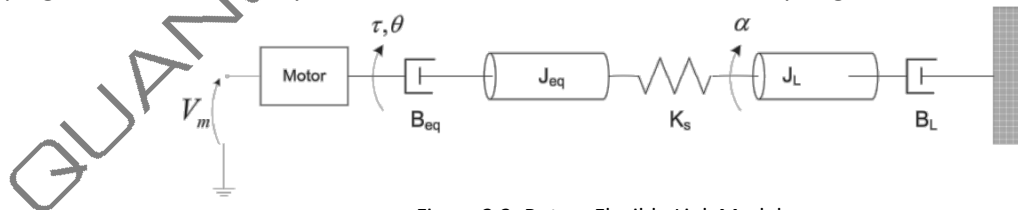

Figure 2.2: Rotary Flexible Link Model

4. PRE-LAB QUESTIONS SECTION - SAMPLE

1. **A-2** Energy is stored in the flexible link, i.e. the "spring", as it rotates by an angle of α (see Figure 2.1). Find the potential energy of the flexible link. Use the parameters shown in Figure 2.2.

   Answer 2.1

Outcome	*Solution*
A-2	*Using the Equation 2.13, the elastic energy stored in the spring equals*

   $$V = \frac{1}{2} K_s \ \alpha^2 \qquad \text{(Ans. 2.1)}$$

   This is the total potential energy that is stored in the system.

2. **A-2** Find the total kinetic energy of the system contributed by the rotary servo, θ, and the deflection in the link, α. Use the parameters shown in Figure 2.2.

   Answer 2.2

Outcome	*Solution*
A-2	*Using the Equation 2.11, the total kinetic energy from the SRV02 rotating and the deflection of this link is*

   $$T = \frac{1}{2} J_{eq} \ \dot{\theta}^2 + \frac{1}{2} J_l \ (\dot{\theta} + \dot{\alpha})^2 \qquad \text{(Ans. 2.2)}$$

3. **A-2** Compute the Lagrangian of the system.

   Answer 2.3

Outcome	*Solution*
A-2	*Using the Equation 2.6, the total kinetic energy from the SRV02 rotating and the deflection of this link is*

   $$L = \frac{1}{2} J_{eq} \ \dot{\theta}^2 + \frac{1}{2} J_l \ (\dot{\theta} + \dot{\alpha})^2 - \frac{1}{2} K_s \alpha^2 \qquad \text{(Ans. 2.3)}$$

COURSEWARE
SAMPLE

ROTARY FLEXIBLE LINK
EXPERIMENT

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5. LAB EXPERIMENTS SECTION - SAMPLE

Control Design

The LQR algorithm discussed in Section 3 is implemented in software to find the control gain that gives the desired closed-loop response. The simulation is performed using the linear state-space model of the system.

Experimental Setup

The FLEXGAGE Control Design VI shown in Figure 3.2 is used to design the feedback control gain using the LQR algorithm. It also simulates the closed-loop response of the Flexible Link using the designed control gain. The VI reads the state-space model from the file that is specified by the user.
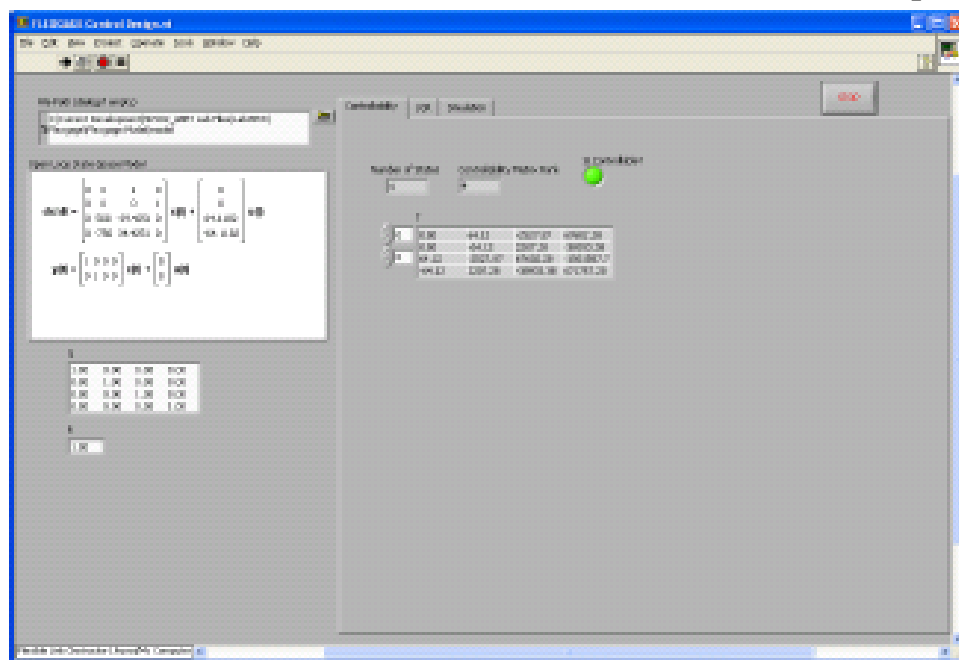

Figure 3.3: VI used to design the state-feedback control gain

IMPORTANT: Before you can conduct this experiment, you need to make sure that the lab files are configured according to your system setup. If they have not been configured already, go to Section 4.2 to configure the files first. Make sure the model you found in Section 2.3.3 is in *File Dialog*.

1. In Rotary Flexible Link (Student).lvproj, open the FLEXGAGE Control Design VI in the Control Design and Simulation folder
2. B-5 Run the VI. It should look similarly as shown in Figure 3.2 (except using your model). The VI will prompt you to find a model file (unless you selected a model in *File Path* already). Find the model you saved from the previous modeling lab.

3. **B-7** Go to the *Controllability Test* tab. Is the system controllable? Explain why.

   Answer 3.6

Outcome	Solution
B-7	The system is controllable because the rank of its controllability matrix equals the number of states.

4. Go the LQR tab. As depicted in Figure 3.3, this computes a feedback gain K according to the model you loaded and the Q and R matrices that are set in the VI. The Q and R are initially set to the default values of:

$$Q = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \text{ and}$$

$$R = 1$$

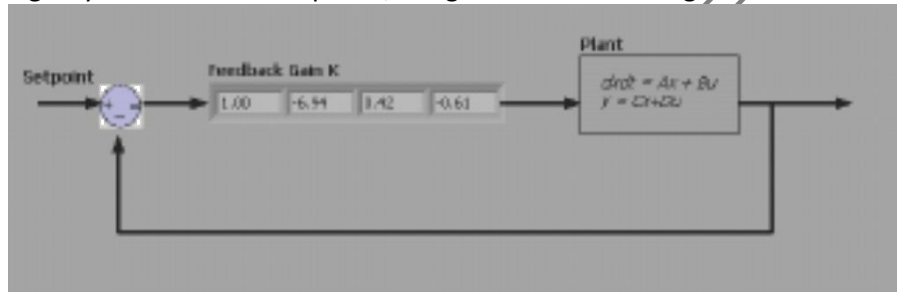   These will not give you the desired response, but generates a default gain *K*.

Figure 3.3: Generated LQR Gain

5. Go the Simulation tab to simulate the closed-loop response with the gain generated back in the LQR tab. The simulated response is shown in Figure 3.4
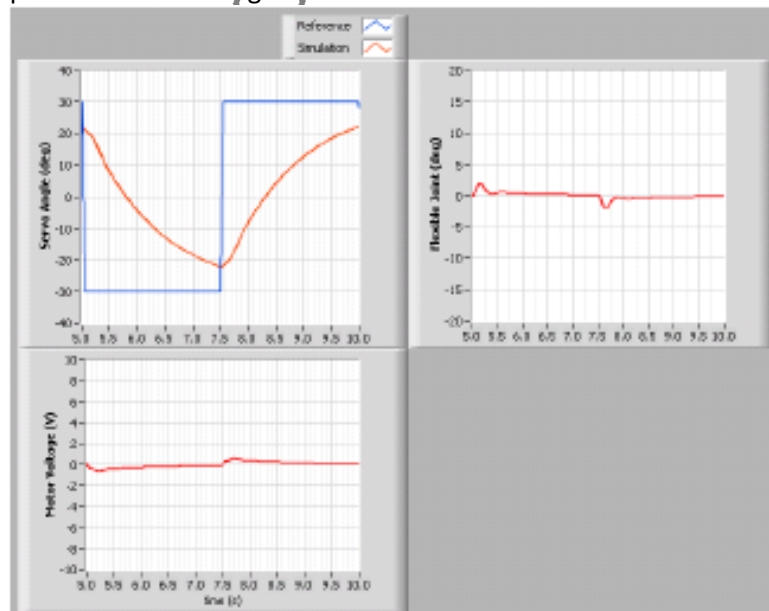

Figure 3.4: Default Simulated Closed-Loop Response

6. B-2   If $Q = diag[q_1; q_2; q_3; q_4]$, vary each q_i independently and examine its effect on the gain and the closed-loop response. For example, when increasing q_3, what happens to θ and α? Vary each q_i by the same order of magnitude and compare how the new gain K changes compared to the original gain. Keep $R = 1$ throughout your testing. Summarize your results.

Note: Recall your analysis in pre-lab Question 3 where the effect of adjusting Q on the generated K was assessed generally by inspecting the cost function equation. You may find some discrepancies in this exercise and the pre-lab questions..

Answer 3.6

Outcome	*Solution*
B-2	*Let $K = [k1\ k2\ k3\ k4]$. The elements effect the gains as follows:*

- *Increasing q_1 increases servo proportional gain k_1. Makes response faster, i.e., decreases peak and settling time.*
- *q_2 does not much effect.*
- *Increasing q_3 increases servo derivative gain k_3. It also makes k_4 more positive. Minimizes overshoot of servo response but also slows it down.*
- *Increasing q_4 decreases the link proportional gain $k2$ and derivative gain k_4. Minimizes deflection of flexible link without affecting the servo related gains, k_1 and k_3, significantly.*

From this exercise, students should identify that the q1 and q4 elements have the greatest effect on the response.

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